ABSTRACT

A wide variety of ion source types has been developed. Ion sources can provide beams of hundreds of amperes for fusion applications, nano–amperes for microprobe trace analysis and broad beams for ion implantation, space thrusters, industrial polymerisation and food sterilisation. Also it can be used in medical, military and accelerators applications. In this paper, three different types of plasma ion sources with different means for producing the discharge current and the ions extracting current from the plasma are studied. The various plasma described include, d.c glow discharge plasma, arc discharge plasma and radio frequency discharge plasma.

Key Words: Ion Sources, Ionization Processes, Sputtering and Etching Processes.

INTRODUCTION

Laboratory plasmas can be created in a wide variety of ways, most commonly as electrical discharges of one kind or another. Industrially, plasmas are used in various forms for semiconductor processing, materials modification and synthesis, and other purposes. In ion sources, plasmas are the medium from which the ions are extracted. Ion sources may be classified according to the discharge and ion beam characteristics.

In general, an ion beam source consists of the ionizer, in which the ions are generated, and of an electrodes system for ion extraction, acceleration and focusing. The ionizer can be operated with gaseous elements or compounds or with liquids or solids vaporized by an external or internal oven, by plasma heating and ion beam sputtering. Positive ions are generated by thermal ionization, photo ionization, field ionization and impact ionization by electrons or ions. The ion beam source is evaluated by: the large ion current extracted from it, the large percentage of ions in the beam, the higher degree of ionization inside the atom, the small gas consumptions, the degree of divergence of the extracted ions must be small and the energy spread in the beam must be small. Over the last decades, special designs have also evolved tailored to different applications in science and technology and several ion beam sources are still a matter of research and development.

Ion sources are employed mostly in particle accelerators, mass spectrometers and ion implantation equipment. These apparatuses are nowadays indispensable tools in scientific research, therapy, technical analyses and in a number of industrial fields.

METHODS OF PLASMA PRODUCTION

Collision processes of positive ions with atoms and molecules may be classified as elastic and inelastic. In an elastic collision, there is no change in the internal energy of the collision
partners. Inelastic collision processes include ionization, stripping, electron capture and excitation of atoms, ions and molecules, for which the internal energy of the collision partners has to be changed. This energy can be distributed among the collision partners or may be converted into internal energy of the products. After an inelastic collision, the internal energy may decrease (exothermic reaction), increase (endothermic reaction) or remain unchanged (resonant reaction). Ionization of neutral atoms to form the plasma state can be accomplished through a number of different processes as, surface ionization (thermal ionization)\(^{(12)}\), photo ionization, field ionization\(^{(13)}\) and laser ionization. Ion sources that do this kind of ionization are called surface ionization sources. Another ionization process, more widely used in the technology of plasma preparation is electron impact\(^{(14)}\), where, in this process, ionization can be produced when an electron collide with a neutral atoms in the gas.

The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization. In this process, a free electron collides with a neutral gas column in which an electric field is applied between two parallel plane electrodes as shown in Fig.(1). This is the phenomenon which occurs after the actual breakdown has taken place. In a Townsend discharge as shown in Fig.(2) the current increases gradually as a function of the applied voltage. Further to the point (B) only the current increases and the discharge changes from the Townsend type to Glow type (BC). Further increase in current results in a very small reduction in voltage across the gap (CD) corresponding to the normal glow discharge. The gap voltage again increases (DE), when the current is increased more, but eventually leads to a significant drop in the applied voltage. This is the region of the arc discharge (EG).

![Fig.(1): Electrical discharge between two parallel plane electrodes.](image1)

![Fig.(2): D.C voltage - current an electrical discharge between two electrodes.](image2)
EXPERIMENTAL RESULTS

Plasma ion sources may be divided according to the types of the used gas discharge. In this work three different types of plasma ion sources, glow discharge ion source, arc discharge ion source and radio frequency ion source, are described. The working principle, discharge characteristics and recent applications of each type of ion sources are discussed.

1- Glow Discharge Ion Source

A compact glow discharge ion source has been designed and constructed in Accelerators and Ion Sources Department, Nuclear Research Center, Atomic Energy Authority. A schematic diagram of the high efficiency glow discharge ion source and its associated electrical circuit is shown in Fig.(3). It consists of aluminium Pierce anode and aluminium plane cathode. The anode has an internal diameter equal to 28 mm at the upper side and 10 mm diameter at the lower side and its length is equal to 17 mm. The aluminium cathode has an aperture of diameter equal to 1.5 mm and length equal to 5 mm. Both the Pierce anode and the plane cathode are immersed in an insulator made of Perspex material. The collector (Faraday cup) is situated at a distance of 5 cm from the ion exit aperture of the cathode and used to measure the output ion beam current by a micrometer. The working gas is admitted to the ion source through the upper side of the anode. A 10 KV power supply is used for initiating the discharge (glow discharge) between the anode and the cathode which is measured using a milliammeter.

![Fig.(3): The glow discharge ion source and its associated electrical circuit.](image)

Figure (4) shows the relation between the output ion beam current, $I_b$, and the discharge voltage, $V_d$, with gap distance, d, between the anode and the cathode at a discharge current, $I_d$, equals to 1.5 mA and a pressure, P, equals to $4.2 \times 10^4$ mmHg using argon gas. It is found that the optimum distance between the anode and the cathode is equal to 5.5 mm, where the maximum output ion beam current and beam energy can be obtained. Also, internal and external operational characteristics have been studied at this optimum distance using hydrogen, nitrogen and argon gases.
Figure (5) shows the relation between the output ion beam current, $I_b$, and the discharge current, $I_d$, at the optimum gap distance between the anode and the cathode and a pressure equals to $4.2 \times 10^{-4}$ mmHg using hydrogen, nitrogen and argon gases. From this figure, it is clear that, at a discharge current equals to 2 mA, the output ion beam current of hydrogen, nitrogen and argon gases are 415, 270 and 195 $\mu$A respectively. This is due to the effect of higher atomic mass of both nitrogen and argon gases than that of hydrogen gas.

This type of glow discharge ion sources is featured by compact size, easy for operation using hydrogen, nitrogen and argon gases, low gas consumption and long life time. The optimum gas pressure is found to be equal to $4.2 \times 10^{-4}$ mmHg, where below this value of gas pressure the instability of the discharge occurs. At operating gas pressure equals to $4.2 \times 10^{-4}$ mmHg, a stable discharge current can be obtained with maximum output ion beam current and energy, i.e. maximum etching rate of any specimen exposed to this ion beam current. Therefore this ion source can be used for etching, sputtering and micro-machining applications.

2- Arc Discharge Ion Source

An example of a high current arc discharge ion source system is the Freeman type ion source which is capable of ionizing the majority of elements of the periodic table, gases, liquids and solid materials. Ion beam current of 12 mA can be obtained using accelerating voltage about 50 KV at low operating pressure. The heavy ion beam injector T-5010 with the Freeman type ion source is used, which is supplied by Efremov Research Institute of Electrophysical Apparatus, Saint Petersburg, Russia. This system has been constructed in Accelerators and Ion Sources Department, Nuclear Research Center, Atomic Energy Authority.

The Freeman ion source and its associated electrical circuit shown in Fig.(6) represent an example of arc discharge, where the arc current between the anode and the cathode is 1 to 6 A and the arc voltage is just 35 to 70 V. It consists of thermo-emission tungsten filament (cathode) surrounding by cylindrical anode made of molybdenum. A cathode rod, usually 2 mm in diameter and made of tantalum or tungsten, is heated with a current varies from 120 – 180 A. The discharge is formed between thermo-emission tungsten filament, cathode, and cylindrical anode.
surrounding it. The applied external permanent magnetic field of about 100 Gauss in the discharge gap is used to help in creation stable plasma and to increase the ionization efficiency.

![Diagram of Freeman ion source with focusing system and its associated electrical circuit.](image)

(A) cylindrical anode rod  (Ext.) extractor electrode  (Ic ) cathode current  (C) cathode rod
(Ia) discharge current supply  (Vd) discharge voltage  (Decel.) deceleration electrode  (P.S) power supply
(I.S) current supply  (B) axial magnetic field  (Accel.) acceleration electrode  (E) emission slit

Fig.(6): Freeman ion source with focusing system and its associated electrical circuit.

The working substances are admitted into the discharge region through three holes in the anode, A, of the source. The working gases are supplied through one hole in the side wall of the anode. Vapors of the working liquids are supplied through another hole from external container. Solid substances having medium or high vaporization temperature are supplied from an internal oven through a hole in the back wall of the arc chamber (anode). The oven is made from molybdenum material. The oven temperature is monitored by mean of a thermocouple.

The ion beams current are extracted from the discharge through an emission slit of 40 mm length and 0.5 – 2 mm wide. The extracted ions of various elements are accelerated in a four electrodes acceleration / deceleration system to obtain energy of up to 40 - 50 KeV. The four electrodes acceleration / deceleration system has two ion accelerating gaps and one ion decelerating gap which allows the ion beam keeping a constant value of beam energy at the ion source outlet. The two accelerating gaps increase the high voltage strength of the system while the decelerating gap reduces the ion beam divergence angle at the ion source outlet. The ion source and the accelerating system are water cooled.

Figure (7) shows the relation between the output ion beam current and the discharge current at a constant pressure, cathode current, Ic , extraction voltage, V_{ext} , and acceleration voltage, V_{acc} , using argon and krypton gases. It is clear that increasing the discharge current leads to increase the output ion beam current and at the same discharge current the value of the
output ion beam current of argon gas is higher than that of krypton gas. This is due to the effect of higher atomic mass of krypton gas than that of argon gas.

Figure (8) shows the relation between the output ion beam current and the acceleration voltage at a constant pressure, cathode current, extraction voltage and discharge current using argon and krypton gases. It is obvious the output ion beam current reaches 11 mA at accelerating voltage equals to 45 KV in case of argon gas while reaches 4.2 mA in case of krypton gas.

Figure (9) shows the relation between the output ion beam current and the discharge current at a constant pressure, cathode current and different oven temperatures, \( T_{\text{oven}} \), using antimony and bismuth solid materials. It is clear that increasing the discharge current leads to increase the output ion beam current and at the same discharge current the value of the output ion beam current in case of antimony is higher than that of bismuth. This is due to the effect of higher atomic mass of bismuth solid material than that of antimony solid material.

Figure (10) shows the relation between the output ion beam current and the acceleration voltage at a constant pressure, cathode current and different oven temperatures, \( T_{\text{oven}} \), using antimony and bismuth solid materials. It is obvious that increasing the accelerating voltage leads to increase the output ion beam current and at the same accelerating voltage the output ion beam current in case of antimony is higher than that for bismuth.
ion beams current for a variety of elements, gases, liquids and solid materials. The excellent performance of the Freeman ion source has made it to be the most successful source for ion implantation, ion beam surface modification of materials, isotope separation and industrial applications, especially for semiconductor purposes. Many companies delivering ion implantation machines supply them with Freeman ion sources. Also Freeman ion source can be used for research in physics and technology of ion beam generation and extraction.

3- Radio Frequency Discharge Ion Source

In practice, the radio frequency (RF) discharge is formed in a vacuum vessel filled with a gas at a pressure of about $10^{-3}$ to $10^{-2}$ mmHg. A few hundred watts of RF power is required to establish a suitable discharge. The discharge is generated by a radio frequency induction coil surrounded vessel filled with a gas (inductively coupled discharge). In this case, electrons present in the vacuum vessel filled with a gas are excited into oscillation by RF electric field. They quickly acquire enough kinetic energy to form plasma by ionizing the gas particles.

Figure (11) shows a schematic diagram of inductively coupled constricted RF ion source with axial extraction. It consists of a Pyrex glass bottle of a diameter 5 cm and constriction at the middle of diameter equal to 4 cm. Pyrex glass bottle is surrounded by the RF - induction coil from the outside and has a tungsten electrode, anode, at the top connected to 10 KV power supply. The anode electrode made of tungsten wire with 1 mm diameter and 5 cm length cover by Pyrex glass insulator to avoid any damage due to electron bombardment. The stainless steel Pierce electrode is fixed at the bottom of a Pyrex glass bottle and connected to earth. The extracted ion beam current emerge through an aperture in the Pierce electrode of radius equal to 2 mm and collected on the Faraday cup which place at a distance equal to 10 cm from the ion exit aperture of Pierce electrode. The inductive coupling and the RF supply to the plasma consists of a copper coil which surrounded the Pyrex glass bottle at the constricted region and is connected to 20 MHz.

![Fig.(11): Schematic diagram of axial constricted RF ion source.](image)

There are three external variables that affect the characteristics of the discharge and the resulting output ion beam current; the gas pressure in the Pyrex glass bottle, the RF field (its magnitude and coupling to the plasma) and the voltage applied to the anode electrode.
Figure (12) shows the variation of the extracted ion beam current, $I_b$, with the voltage, $V$, applied to the anode electrode at constant pressure and RF power using nitrogen and argon gases. It is clear that the extracted ion beam current increases with increasing the voltage applied to the anode electrode according to the Child–Langmuir law. This means that the ion beam current which can be extracted from the plasma boundary exhibits a $V_{ext}^{3/2}$ dependence. Also, it is obvious that at constant anode voltage, RF power, RF oscillator and pressure, the extracted ion beam current of nitrogen gas is higher than in case of argon gas. This is due to the higher atomic mass of argon gas than that of nitrogen gas.

![Graph](image)

**Fig.(12): The output ion beam current versus anode voltage using nitrogen and argon gases.**

Figure (13) shows the output ion beam current, $I_b$, versus gas pressure, $P$, at constant RF power and anode voltage using nitrogen and argon gases. It is clear that by increasing the gas pressure the extracted ion beam current decreases. This is due to the decrease of the mean free path of the oscillating electrons. Therefore in order to keep the extracted ion beam current constant, the RF power must be increased. This is due to increase of ionization density by increasing RF power.

![Graph](image)

**Fig.(13): The output ion beam current gas pressure at constant RF power and anode voltage using nitrogen and argon gases.**

The RF ion sources have many advantages such as; its clean resulting from the absence of metallic surfaces in the discharge, high proton percentages (up to 90%), operation at low pressure yields a higher efficiency with respect to gas consumption and simplicity of construction and maintenance. The RF ion sources can be used in research applications such as cyclotrons, synchrotrons, neutral beam injectors for fusion research and production of multiply charged ions. Also it can be used in industrial applications such as ion implantation system, ion beam etching, ion beam doping, ion beam lithography, material surface modification and proton therapy machines.
CONCLUSION

In this paper, the most commonly used methods for the generation of plasma for technological applications are reviewed. Also, three different kinds of ion sources with different discharge types which have been constructed in Accelerators and Ion Sources Department, Nuclear Research Center, Atomic Energy Authority are used. It is concluded that each type of ion sources is characterized by a certain range of discharge current and output ion beam current. Therefore, a selection of positive ion source type is usually depending on the specific application of the corresponding accelerated ion beams.

REFERENCES


